Effects of variation of fundamental constants from Big Bang to atomic clocks

Contributors:

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The possibility for the fundamental constants to vary is suggested by theories unifying **gravity** with **other** interactions.

Fine structure constant $\alpha = e^2/\hbar c$,
e -electron charge, c -speed of light.
Quark mass m_q/Strong interaction scale Λ_{QCD}.

The search goes in:

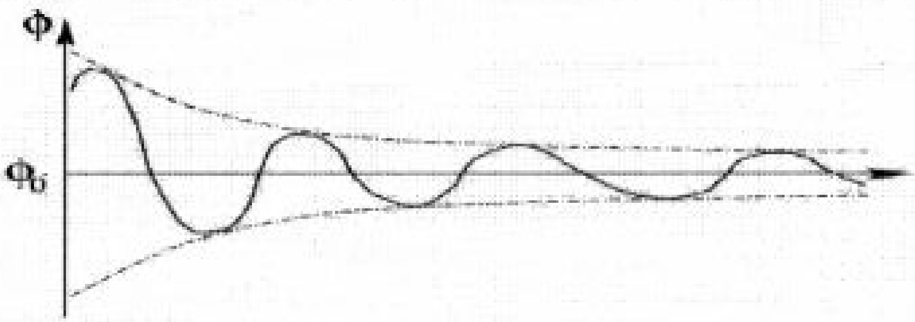
(1) Quasar absorption spectra (QAS)
(2) Big Bang Nucleosynthesis (BBN)
(3) Oklo natural nuclear reactor
(4) Atomic clocks

	Constants			Result
QAS	α	$\frac{m_q}{\Lambda_{QCD}}$		$\Delta \neq 0$!?
BBN	α	$\frac{m_q}{\Lambda_{QCD}}$	$\frac{\Lambda_{QCD}}{M_{Plank}}$	$\Delta \neq 0$!?
Oklo	α	$\frac{m_q}{\Lambda_{QCD}}$		$\Delta \neq 0$!?
Clocks	α	$\frac{m_{q,e}}{\Lambda_{QCD}}$		$\Delta < \delta$

"Motivating" comments from the literature:

- "Unified theories applied to cosmology suffer generically from a problem of predicting time-dependent coupling constants." – Fujii Y.,Omote M.,Nishakoa T.,1994,Prog.Theor.Phys.,92,3
- " … in cosmology with extra dimensions people try to find solutions with the external dimensions expanding while the extra dimensions remain static. But at present no mechanism for keeping the internal spatial scale static has been found." – Li L. –X, Gott J. R. III, 1998, Phys. Rev. D, 58, 103513 $\alpha \propto G / R_{KK}^2$
- " … $dR_{KK}/dt \neq 0$ … could give rise to observable time variations in the fundamental "constants" of our four-dimensional world and thereby provide a window to the extra dimensions." – Marciano W. J., 1984, Phys. Rev. Lett., 52, 489
- " … all coupling constants and masses of elementary particles, being dependent on the dilaton scalar field, should be, generally speaking, space and time dependent, and influenced by local circumstances." – Damour T., Polyakov A. M., 1994, Nucl. Phys. B, 423, 532

$\alpha = \alpha(\phi)$



- $\alpha = e^2/\hbar c$ - " The minimal varying-*c* theory is of interest because it offers a means of solving the so-called cosmological problems: the horizon, flatness,cosmological constant, entropy, and homogeneity problems."–Barrow J. D., Magueijo J., 1998, Phys. Lett. B, 443, 104

Some special "tuning" of fundamental constants is neeeded for humans to exist.

Example: low-energy resonance in carbon production reaction in stars:

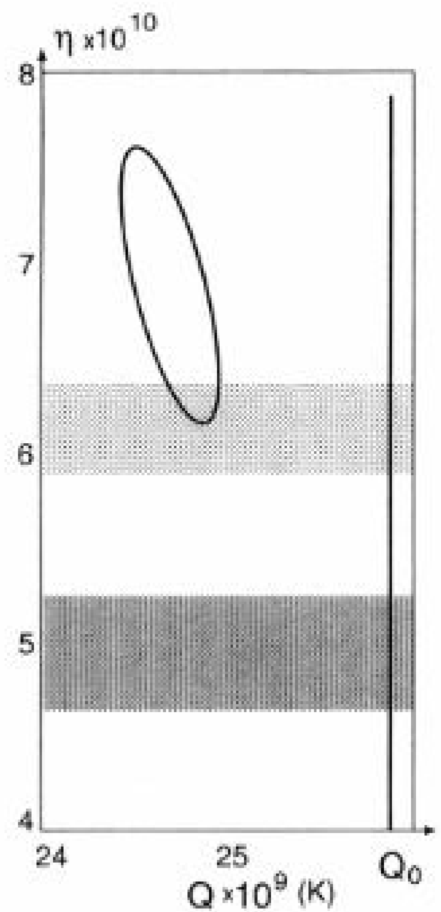
$$^4He+^4He+^4He=^{12}C$$

Different coupling constants $\rightarrow$ no low-energy resonance $\rightarrow$ no carbon $\rightarrow$ no life.

Variation of coupling constants in space could provide a natural explanation of "fine tuning": we appeared in area of the Universe where values of fundamental constants are consitent with our existence.

Big Bang Nucleosynthesis

(Dmitriev, Flambaum, Webb)



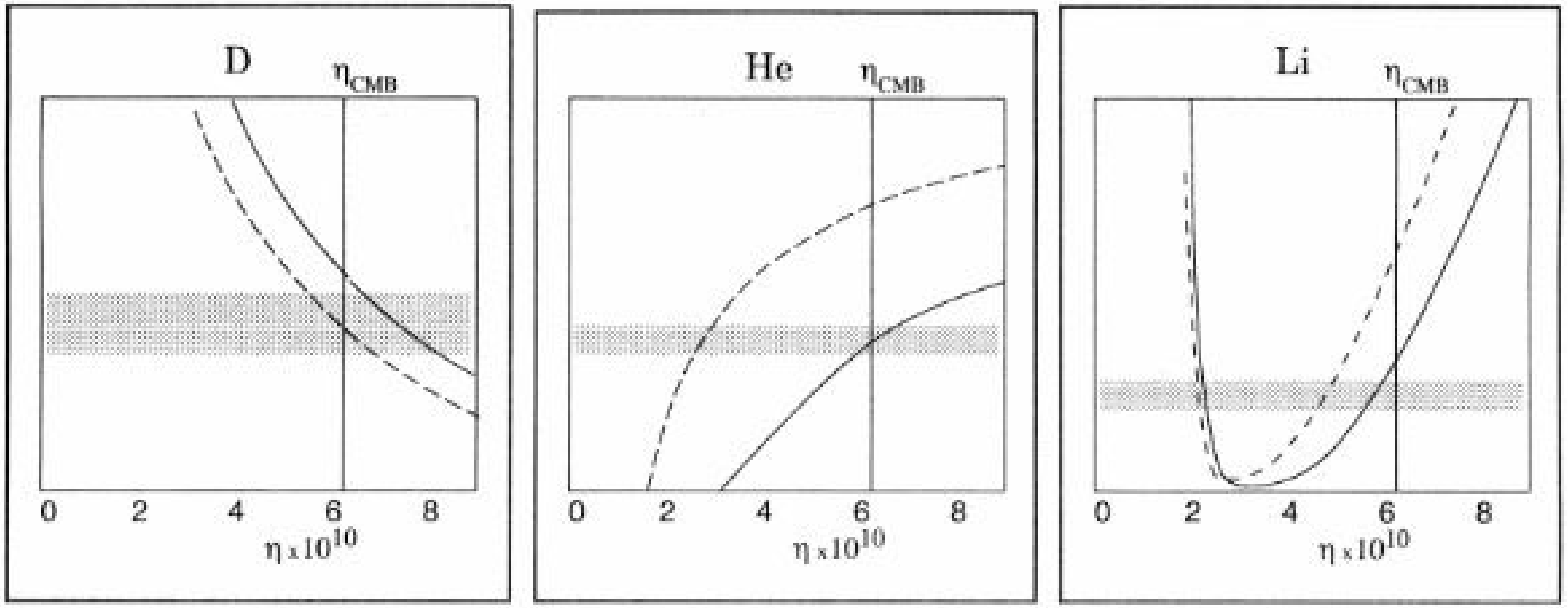
$$p + n \to d + \gamma, \quad 3 \text{ sec} \leq \text{t} \leq 6 \text{ min}$$

Productions of D, ^{4}He, ^{7}Li are exponentially sensitive to deuteron binding energy E_d

$$\sim e^{-\frac{E_d}{T_f}}$$

- η from cosmic microwave background fluctuations (η - barion to photon ratio).

- η from BBN for present value of Q ($Q = |E_d|$)



Comparison with observations gives

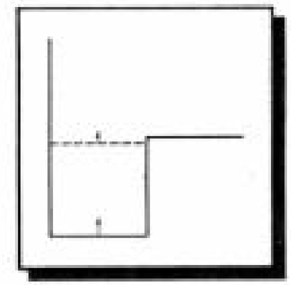
$$\frac{\delta E_d}{E_d} = -0.019 \pm 0.005$$

This also leads to agreement

$$\eta(BBN) \approx \eta(CMB)$$

Flambaum, Shuryak: Deuteron Binding Energy is very sensitive to variation of *strange* quark mass (4 factors of enhancement):

1. Deuteron is a shallow bound level.

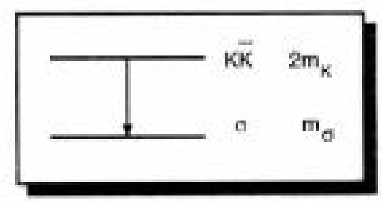


Virtual level in $n+p \rightarrow d+\gamma$ is even more sensitive to the variation of the potential.

2. Strong compensation between σ-meson and ω-meson exchange in potential (Walecka model): $4\pi r V = -g_s^2 e^{-m_\sigma r} + g_v^2 e^{-m_\omega r}$

3. $\sigma = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$, $\quad m_\sigma \approx \frac{2}{3} m_s + 2\Lambda_{QCD}$

4. Repulsion of σ from $K\overline{K}$ threshold



Total $\frac{\delta E_d}{E_d} \approx -17 \frac{\delta m_s}{m_s}$ and $\frac{\delta(m_s/\Lambda_{QCD})}{m_s/\Lambda_{QCD}} = (+1.1 \pm 0.3) \times 10^{-3}$

Sensitivity of E_d to variation of of the light quark mass m_q

Pion mass $m_\pi \sim \sqrt{m_q \cdot \Lambda_{QCD}}$

$$\frac{\delta E_d}{E_d} = K_\pi \frac{\delta m_\pi}{m_\pi} = K_\pi \cdot \frac{1}{2} \cdot \frac{\delta m_q}{m_q}$$

Flambaum, Shuryak 2002

$$-18 < K_\pi < 3$$

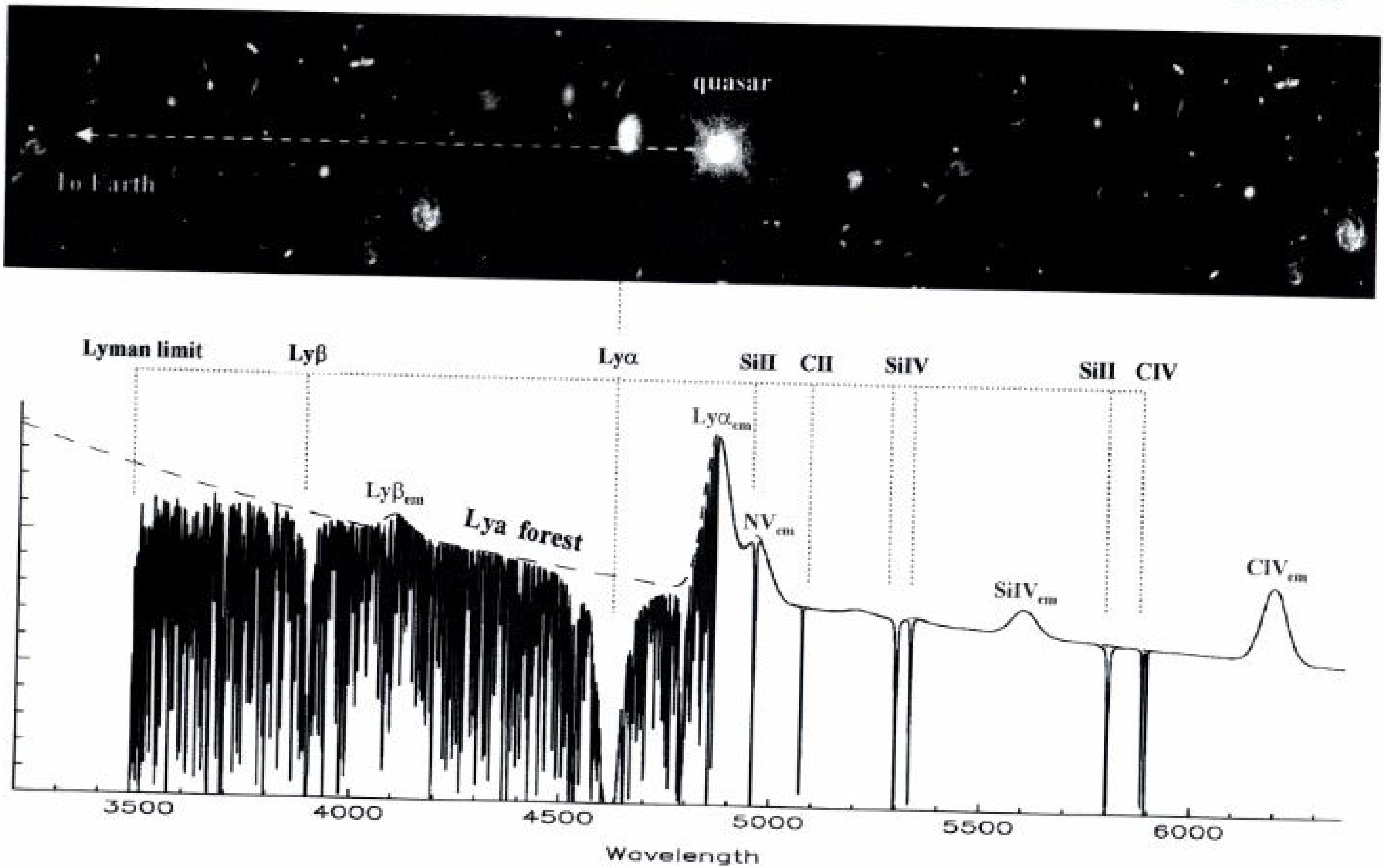
Epelbaum
Meißner, Glöckle

$$\frac{\partial E_d}{\partial m_\pi} = -0.075 \pm 0.023$$

$$\longrightarrow \quad K_\pi = -5 \; (1 \pm 0.3)$$

$$\frac{\delta E_d}{E_d} \simeq -2.5 \; \frac{\delta (m_q / \Lambda_{QCD})}{(m_q / \Lambda_{QCD})}$$

4.2 Astrophysical constraints: Quasars - probing the universe back to much earlier times



Many-Multiplet Method

Relativistic correction to electron energy E_n:

$$\Delta_n = \frac{E_n}{\nu}(Z\alpha)^2\left[\frac{1}{j+1/2} - C(Z,j,l)\right] \quad C \approx 0.6$$

1. Increases with nuclear charge Z.
2. Changes sign for higher angular momemtum j.

Procedure:

1. **Compare heavy (Z~30) and light (Z<10) atoms, OR**
2. **Compare s → p and d → p transitions in heavy atoms.**

Shifts can be of opposite sign.

Basic formula:

$$E_z = E_{z=0} + q\left[\left(\frac{\alpha_z}{\alpha_0}\right)^2 - 1\right]$$

$E_{z=0}$ is the laboratory frequency. 2nd term is non-zero only if α has changed. q is derived from atomic calculations.

Relativistic shift of the central line in the multiplet → $q = Q + K(L.S)$ ← **K is the spin-orbit splitting parameter. Q ~ 10K**

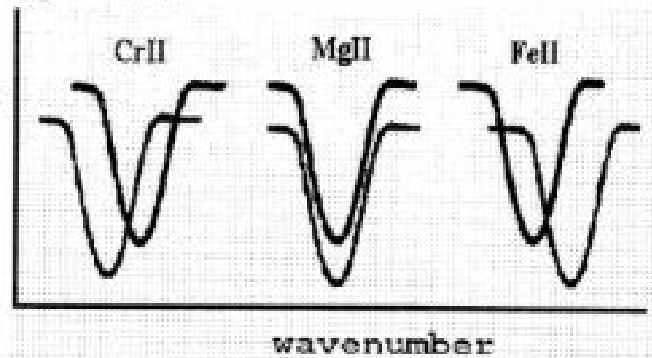
Numerical examples: (units = cm^{-1})

Z=26 (s → p) FeII 2383A: ω_0 = 38458.987(2) + 1449x

Z=12 (s → p) MgII 2796A: ω_0 = 35669.298(2) + 120x

Z=24 (d → p) CrII 2066A: ω_0 = 48398.666(2) - 1267x

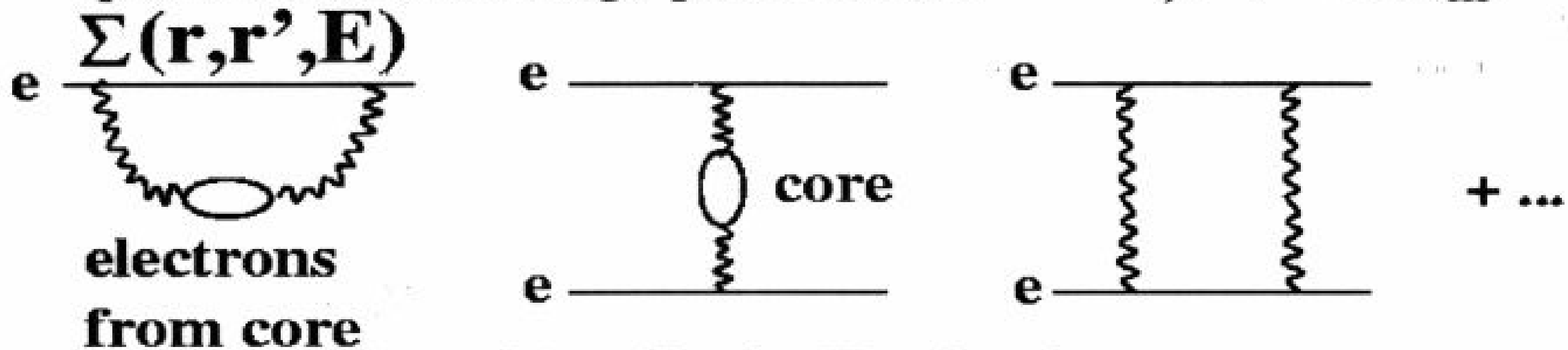
$x = (\alpha_z/\alpha_0)^2 - 1$



MgII "anchor"

To find dependence of atomic transition frequencies on α we have performed calculations of atomic transition frequencies for different values of α.

1. **Zero Approximation – Relativistic Hartree-Fock method: energies, wave functions, Green's functions**
2. **Many-body perturbation theory to calculate effective Hamiltonian for valence electrons including self-energy operator and screening; perturbation ⟶ $V = H - H_{\mathrm{HF}}$**



3. **Diagonalization of the effective Hamiltonian**

Test: Energy levels in Mg II to 0.2% accuracy

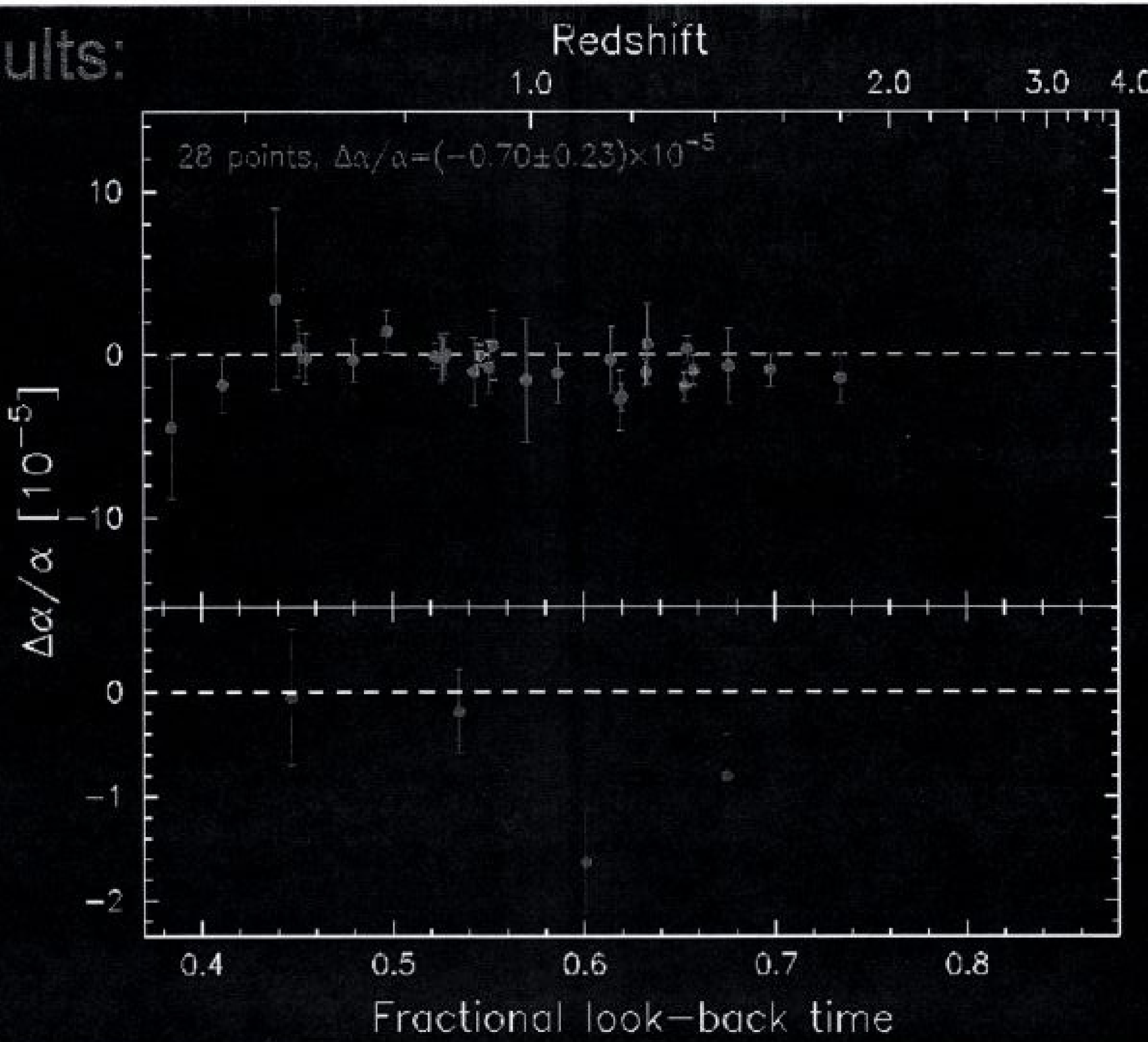
Lines used in the analysis (cm^{-1})

Anchor lines				Negative shifters			
MgI	35051.277(1)	+	$86x$	NiII	57420.013(4)	-	$1400x$
MgII	35760.848(2)	+	$211x$	NiII	57080.373(4)	-	$700x$
MgII	35669.298(2)	+	$120x$	CrII	48632.055(2)	-	$1110x$
SiII	55309.3365(4)	+	$520x$	CrII	48491.053(2)	-	$1280x$
SiII	65500.4492(7)	+	$50x$	CrII	48398.868(2)	-	$1360x$
AlII	59851.924(4)	+	$270x$	FeII	62171.625(4)	-	$1300x$
AlIII	53916.540(1)	+	$464x$	Positive shifters			
AlIII	53682.880(2)	+	$216x$	FeII	62065.528(3)	+	$1100x$
NiII	58493.071(4)	-	$20x$	FeII	42658.2404(2)	+	$1210x$
				FeII	42114.8329(2)	+	$1590x$
				FeII	41968.0642(2)	+	$1460x$
				FeII	38660.0494(2)	+	$1490x$
				FeII	38458.9871(2)	+	$1330x$
				ZnII	49355.002(2)	+	$2490x$
				ZnII	48481.077(2)	+	$1584x$

$$\omega = \omega_{Lab} + qx$$

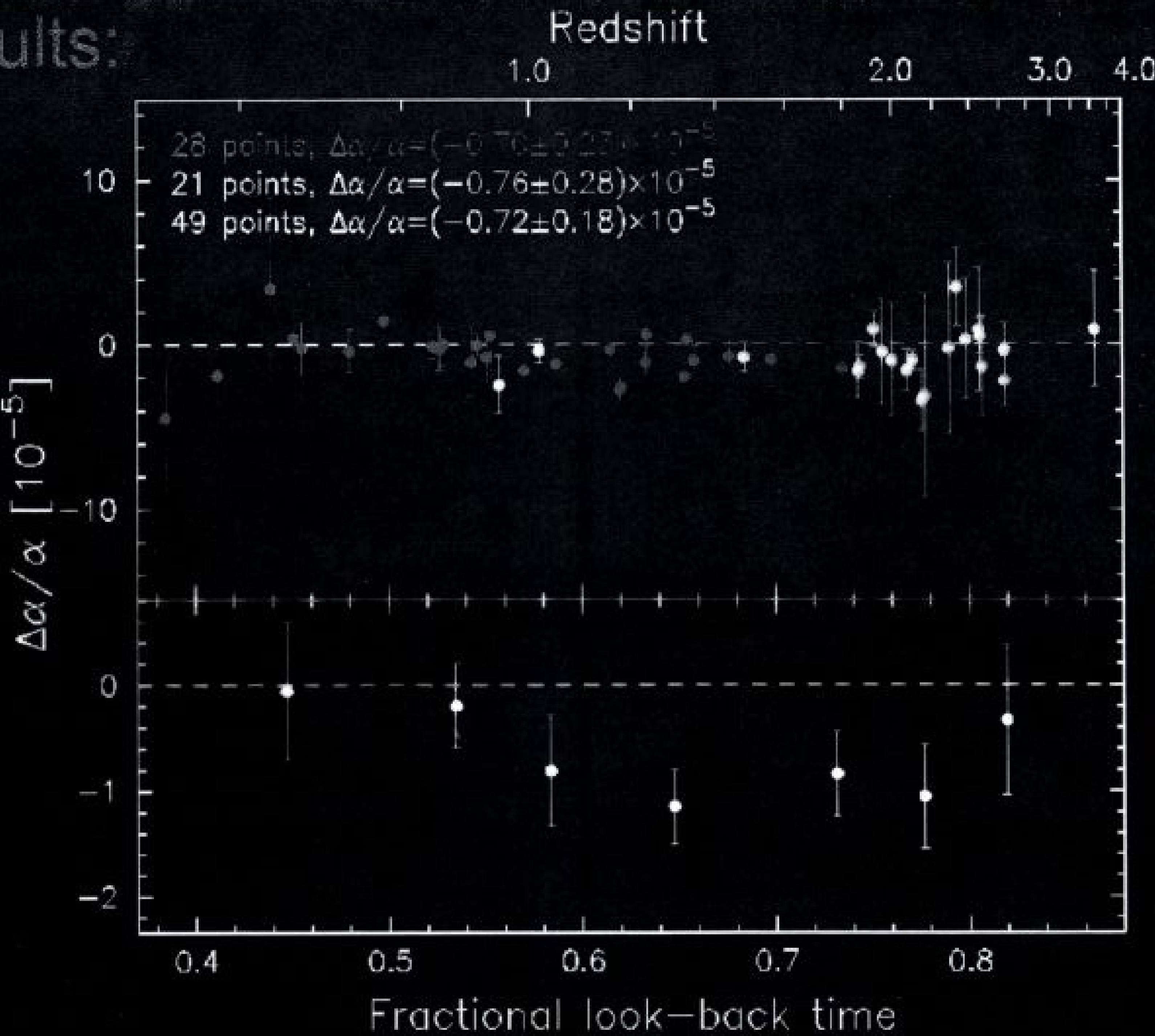
$$x = \frac{\alpha^2}{\alpha_{Lab}^2} - 1$$

Results:

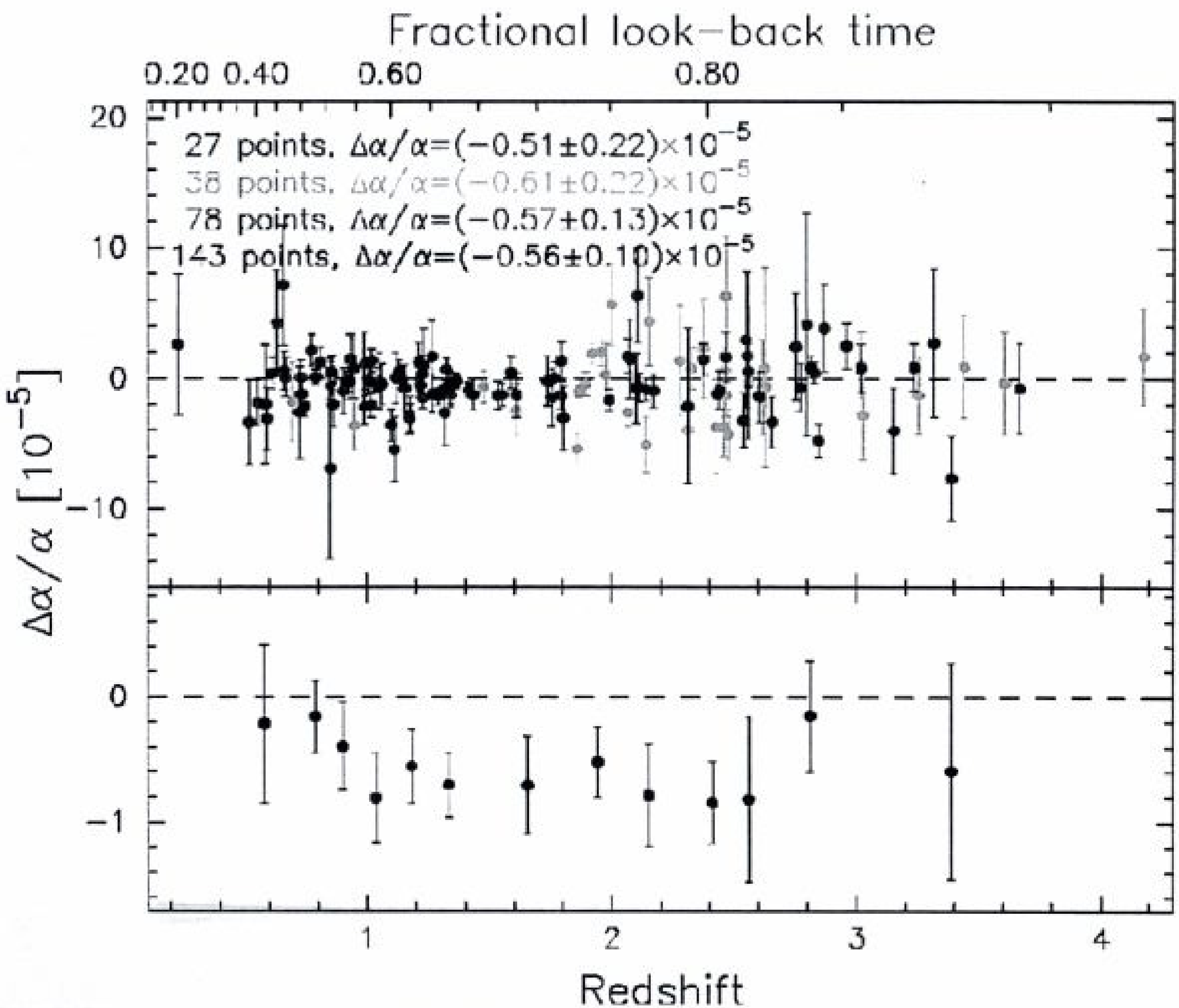


Redshift
1.0
2.0
3.0
4.0
28 points, Δα/α=(−0.70±0.23)×10^{-5}
10
0
−10
Δα/α [10^{-5}]
0
−1
−2
0.4
0.5
0.6
0.7
0.8
Fractional look−back time

Results:



Redshift
1.0
2.0
3.0
4.0
28 points, Δα/α=(−0.70±0.23)×10^−5
21 points, Δα/α=(−0.76±0.28)×10^−5
49 points, Δα/α=(−0.72±0.18)×10^−5
10
0
−10
0
−1
−2
Δα/α [10^−5]
0.4
0.5
0.6
0.7
0.8
Fractional look−back time



Fractional look-back time
0.20 0.40 0.60 0.80
27 points, Δα/α=(−0.51±0.22)×10⁻⁵
38 points, Δα/α=(−0.61±0.22)×10⁻⁵
78 points, Δα/α=(−0.57±0.13)×10⁻⁵
143 points, Δα/α=(−0.56±0.10)×10⁻⁵
Δα/α [10⁻⁵]
20
10
0
−10
0
−1
1
2
3
4
Redshift

Potential systematic effects:

- ☺ Wavelength calibration errors
- ☺ Laboratory wavelength errors
- ☺ Heliocentric velocity variation
- ☺ Temperature changes during observations
- ☺ Line blending
- ☺ Differential isotopic saturation
- ☺ Hyperfine structure effects
- ☺ Instrumental profile variations
- ☺ … and of course, Magnetic fields
- ☹ ~~Atmospheric dispersion effects~~
- ☹ Isotopic ratio evolution

UVES QSO Sample 2004

Wilfred Walsh, John Webb, Victor Flambaum
wwalsh@phys.unsw.edu.au

UNIVERSITY OF NEW SOUTH WALES
SYDNEY AUSTRALIA

UNSW, September 2004

Results:

1998-2003, Keck telescope, Hawaii, red shift $0.2 < z < 4.3$, 143 absorption systems, 23 transitions, 3 independent samples:

$\frac{\delta\alpha}{\alpha} = (-0.543 \pm 0.116) \cdot 10^{-5}$

Statistical significance 4.7 σ from zero.

2004, VLT-UVES, Chile (different hemisphere), red shift $0.4 < z < 2.8$

full sample, 74 systems $\frac{\delta\alpha}{\alpha} = (-0.020 \pm 0.092) \cdot 10^{-5}$

clean sample, 52 systems $\frac{\delta\alpha}{\alpha} = (-0.004 \pm 0.098) \cdot 10^{-5}$

Strianand et al sample, 23 systems $\frac{\delta\alpha}{\alpha} = (-0.061 \pm 0.126) \cdot 10^{-5}$

VLT: $|\frac{\delta\alpha}{\alpha}| < 0.1 \cdot 10^{-5}$. Zero!

Too large scatter, more realistic preliminary result

$\frac{\delta\alpha}{\alpha} = (-0.05 \pm 0.29) \cdot 10^{-5}$

Other groups results from VLT-UVES:

Strianand, Chand, Petitjean, Aracil (2004), 23 systems, 12 transitions, $0.4 < z < 2.3$:

$\frac{\delta\alpha}{\alpha} = (-0.06 \pm 0.06) \cdot 10^{-5}$

Quast, Reimer, Levshakov (2004): 1 system, Fe II only, 6 transitions, $z = 1.15$:

$\frac{\delta\alpha}{\alpha} = (-0.04 \pm 0.19 \pm 0.27_{syst}) \cdot 10^{-5}$

Difference between Keck and VLT data:

Undiscovered systematic effect?

Spatial variation of α?

C. L. Steinhardt, Phys. Rev. D, 71, 043509 (2005):
It might be spatial variation!

Srianand et al use data from Southern Hemisphere only

$$(\frac{\Delta\alpha}{\alpha})_{\text{South}} = (-0.06 \pm 0.06) \times 10^{-5}$$

Murphy et al use both:

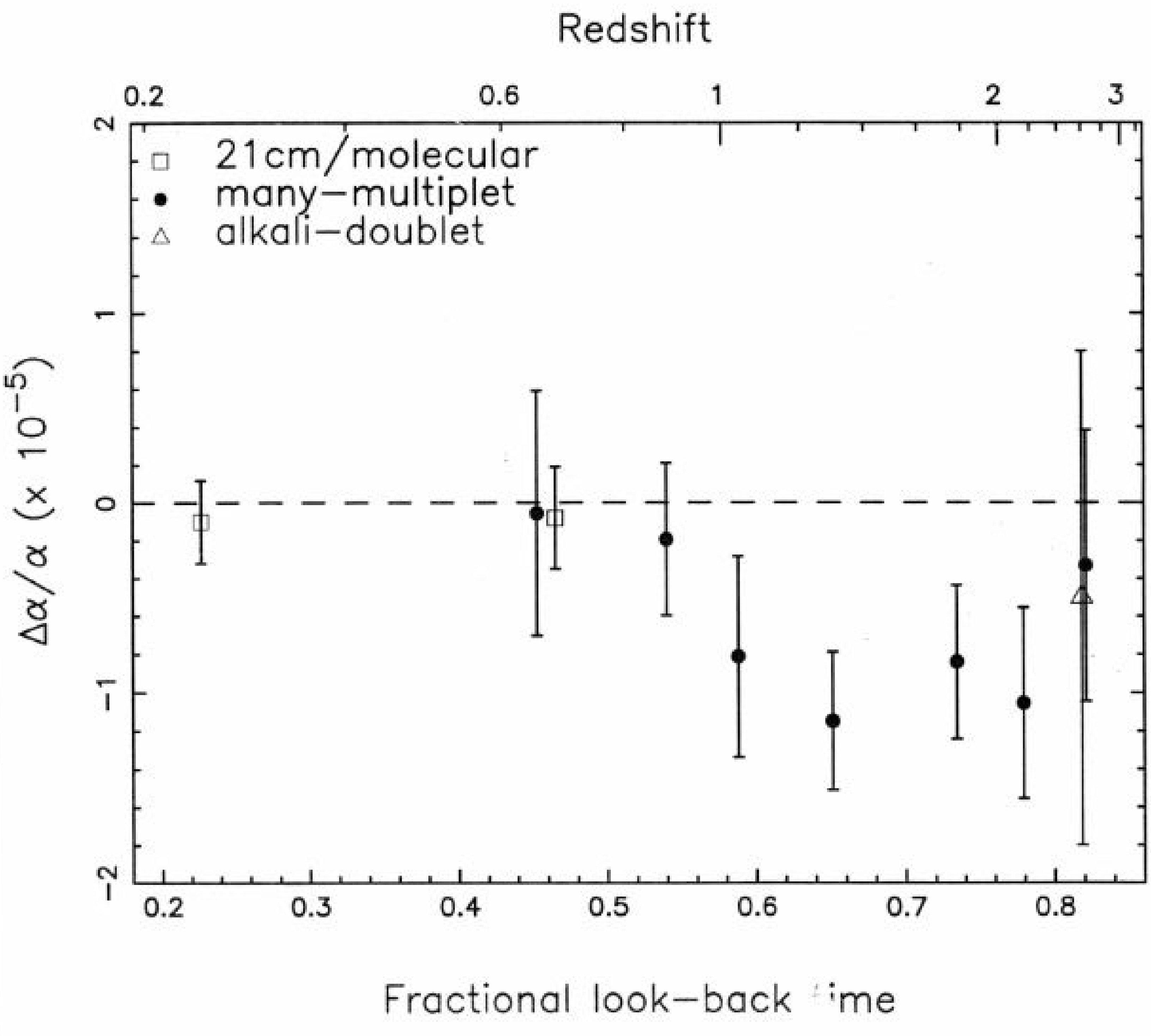
$$(\frac{\Delta\alpha}{\alpha})_{\text{South}} = (-0.36 \pm 0.19) \times 10^{-5}$$

$$(\frac{\Delta\alpha}{\alpha})_{\text{North}} = (-0.66 \pm 0.12) \times 10^{-5}$$

Radio constraints:

- Hydrogen hyperfine transition at $\lambda_H = 21$cm.
- Molecular rotational transitions CO, HCO^+, HCN, HNC, CN, CS …
- $\omega_H/\omega_M \propto \alpha^2 g_P$ where g_P is the proton magnetic g-factor.

$$g_p = g_p\left(\frac{m_q}{\Lambda_{QCD}}\right)$$


Redshift
0.2
0.6
1
2
3
21cm/molecular
many-multiplet
alkali-doublet
Δα/α (x 10⁻⁵)
2
1
0
−1
−2
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Fractional look-back time

ur Measurments

$$\frac{\delta(\alpha^2 g_p)}{(\alpha^2 g_p)} = \frac{\delta X}{X} = (-0.16 \pm 0.54) \cdot 10^{-5}$$

$z \simeq 0.7$, 6 bn years ago

$$X = \alpha^2 \left(\frac{m_q}{\Lambda_{QCD}} \right)^{-0.09}$$

Flambaum
Leinweber
Thomas
Young

GUT models:

Calmet, Fritzsch; Langecker, Segre, Strassl

$$\frac{\delta(m/\Lambda_{QCD})}{m/\Lambda_{QCD}} \sim 35 \frac{\delta\alpha}{\alpha}$$

weak / strong variation
may be more important!

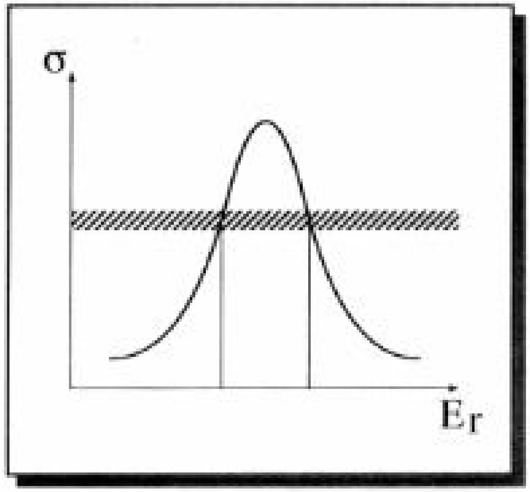
Measurements of $m_e/m_p \sim m_e/\Lambda_{QCD}$

Tsanavaris,Webb,Murphy,Flambaum,Curran
Phys.Rev.Lett. 2005
hyperfine 21 cm H/optical
Mg,Ca,Mn,Ti,C,Si,Zn,Cr,Fe,Ni
8 quasar absorption systems, $0.24 < z < 2.04$
Measured $X = \alpha^2 g_p m_e/m_p$
$\frac{\delta X}{X} = (1.17 \pm 1.01)10^{-5}$
$\frac{dlnX}{dt} = (-1.43 \pm 1.27)10^{-15}/year$
No variation.

Combined with measurements of α-variation
$\frac{\delta(m_e/m_p)}{(m_e/m_p)} = (2.31 \pm 1.03)10^{-5}$
$\frac{\delta(m_e/m_p)}{(m_e/m_p)} = (1.29 \pm 1.01)10^{-5}$
Recent result based on H_2 measurements
Reinhold,Bunning,Hollenstein,Ivanchik,Petitjean, Ubach 2005.
$\frac{\delta(m_e/m_p)}{(m_e/m_p)} = (-2.4 \pm 0.6)10^{-5}$
Variation 4σ!

Oklo natural nuclear reactor

S. Lamoreax and J. Torgerson, nucl-th/0309048 PRD(2004)



$n + ^{149}\mathrm{Sm} \rightarrow ^{150}\mathrm{Sm}$ cross-section.

Two solutions for the change of the resonance position E_r:

1. $\Delta E_r = (-135 \pm 5) \times 10^{-3}$ eV
2. $\Delta \mathrm{E_r} = (-58 \pm 5) \times 10^{-3}$ eV

V. Flambaum and E. Shuryak, hep-ph/0212403: PRD (2004)

$$\Delta E_r = 1.7 \times 10^8 \mathrm{eV} \, \frac{\delta(\mathrm{m_s}/\Lambda)}{\mathrm{m_s}/\Lambda}$$

1. $\frac{\delta(m_s/\Lambda)}{m_s/\Lambda} = (-0.80 \pm 0.03) \times 10^{-9}$
2. $\frac{\delta(m_s/\Lambda)}{m_s/\Lambda} = (-0.34 \pm 0.03) \times 10^{-9}$

$1.8 \cdot 10^9$ years ago

LABORATORY EXPERIMENTS - ATOMIC CLOCKS

There are two types of atomic clocks:

1. Microwave (e.g. ^{133}Cs, 6s hfs F=3 - F=4 transition serves as definition of metric second; also Rb, Yb^+, etc.).

2. Optical (Ca, Sr, Hg $^1S_0 - ^3P_1$, etc.)

Comparing rates of different clocks allows to study variation of fundamental constants.

Advantages:

1. Very narrow lines, sensitivity in $\frac{\Delta\alpha}{\alpha}$ up to 10^{-18} per year.

2. Larger Z, q up to 60000 cm^{-1}.

3. Simple interpretation ($\dot{c}/c\mid_{t=today}$).

Optical atomic clocks

TABLE II: Experimental energies and calculated q coefficients for transitions from the ground state to the state shown.

Atom/Ion	Z	State		Wavelength, Å Experiment	q (cm^{-1})	Reference
Al II	13	$3s3p$	$^3P_0$	2674.30	146	[12]
		$3s3p$	$^3P_1$	2669.95	211	[12]
		$3s3p$	$^3P_2$	2661.15	343	[12]
		$3s3p$	$^1P_1$	1670.79	278	[12]
Ca I	20	$4s4p$	$^3P_0$	6597.22	125	[12]
		$4s4p$	$^3P_1$	6574.60	180	[12]
		$4s4p$	$^3P_2$	6529.15	294	[12]
		$4s4p$	$^1P_1$	4227.92	250	[12]
Sr I	38	$5s5p$	$^3P_0$	6984.45	443	[12]
		$5s5p$	$^3P_1$	6894.48	642	[12]
		$5s5p$	$^3P_2$	6712.06	1084	[12]
		$5s5p$	$^1P_1$	4608.62	924	[12]
Sr II	38	$4d$	$^2D_{3/2}$	6870.07	2828	[9]
		$4d$	$^2D_{5/2}$	6740.25	3172	[9]
In II	49	$5s5p$	$^3P_0$	2365.46	3787	[12]
		$5s5p$	$^3P_1$	2306.86	4860	[12]
		$5s5p$	$^3P_2$	2182.12	7767	[12]
		$5s5p$	$^1P_1$	1586.45	6467	[12]
Ba II	56	$5d$	$^2D_{3/2}$	20644.74	5844	[13]
		$5d$	$^2D_{5/2}$	17621.70	5976	[13]
Dy I	66	$4f^{10}5d6s$	$^3[10]_{10}$	5051.03	6008	[14]
		$4f^9 5d^2 6s$	$^9K_{10}$	5051.03	-23708	[14]
Yb I	70	$6s6p$	$^3P_0$	5784.21	2714	[12]
		$6s6p$	$^3P_1$	5558.02	3527	[12]
		$6s6p$	$^3P_2$	5073.47	5883	[12]
		$6s6p$	$^1P_1$	3989.11	4951	[12]
Yb II	70	$4f^{14}5d$	$^2D_{3/2}$	4355.25	10118	[14]
		$4f^{14}5d$	$^2D_{5/2}$	4109.70	10397	[14]
		$4f^{13}6S^2$	$^2F_{7/2}$	4668.81	-56737	[14]
Yb III	70	$4f^{13}5d$	$^3P_0$	2208.63	-27800	[14]
Hg I	80	$6s6p$	$^3P_0$	2656.39	15299	[12]
		$6s6p$	$^3P_1$	2537.28	17584	[12]
		$6s6p$	$^3P_2$	2270.51	24908	[12]
		$6s6p$	$^1P_1$	1849.50	22789	[12]
Hg II	80	$5d^9 6s^2$	$^2D_{5/2}$	2815.79	-56671	[9]
		$5d^9 6s^2$	$^2D_{3/2}$	1978.16	-44003	[9]
Tl II	81	$6s6p$	$^3P_0$	2022.20	16267	[12]
		$6s6p$	$^3P_1$	1872.90	18845	[12]
		$6s6p$	$^3P_2$	1620.09	33268	[12]
		$6s6p$	$^1P_1$	1322.75	29418	[12]
Ra II	88	$6d$	$^2D_{3/2}$	8275.15	18785	[13]
		$6d$	$^2D_{5/2}$	7276.37	17941	[13]

Table 99.1. Relative sensitivity of the hyperfine relativistic factors to the variation of α (parameter κ) and nuclear magnetic moments on the variation of the quark mass/strong interaction scale m_q/Λ_{QCD} (parameter β) for atoms involved in microwave standards.

Z	Atom	κ	β
1	^1H	0.00	-0.100
1	^2H	0.00	-0.063
37	^{87}Rb	0.34	-0.074
48	$^{111}Cd^+$	0.6	-0.117
55	^{133}Cs	0.83	0.127
70	$^{171}Yb^+$	1.5	-0.117
80	$^{199}Hg^+$	2.3	-0.117

Using parameters κ and *beta* we can present dependence of the microwave standards on the fundamental constants:

$$\frac{\partial \ln f}{\partial t} = \frac{\partial \ln V}{\partial t} \tag{99.5}$$

$$V = cR_\infty \cdot \frac{m_e}{m_p} \cdot \alpha^{2+\kappa} \cdot \left(\frac{m_q}{\Lambda_{QCD}}\right)^\beta \tag{99.6}$$

In comparison of two microwave standards the factors cR_∞ and m_e/m_p are cancelled out. However, in comparison of optical and microwave standards the factor m_e/m_p survives. Its dependence on the fundamental constants is the following

$$\partial \ln \frac{m_e}{m_p} = \partial \ln\left[\frac{m_e}{\Lambda_{QCD}} \cdot \left(\frac{m_q}{\Lambda_{QCD}}\right)^{-0.048}\right] \tag{99.7}$$

We may assume that the electron mass and all quark masses have the same relative variation . This assumption seems to be natural if the Higgs mechanism of mass generation is correct.

Comparing atomic clocks one can study:

Atomic	optical/optical	α^2
	optical/hyperfine	α^2, $m_{e,q}/\Lambda_{QCD}$
	hyperfine/hyperfine	" "
Molecular	hyperfine/rotational	" "
	hyperfine/Λ-doubling	" "
	rotational/optical	" "

Experiment			$\frac{1}{\alpha}\frac{d\alpha}{dt}(10^{-15}/\text{year})$
Marion et al	2003	$\frac{\text{Rb(hfs)}}{\text{Cs(hfs)}}$	$(0.05 \pm 1.3)^a$
Bize et al	2003	$\frac{\text{Hg}^+\text{(opt)}}{\text{Cs(hfs)}}$	$(-0.03 \pm 1.2)^a$
Fisher et al	2004	$\frac{\text{H(opt)}}{\text{Cs(hfs)}}$	$(-1.1 \pm 2.3)^a$
Peik et al	2004	$\frac{\text{Yb}^+\text{(opt)}}{\text{Cs(hfs)}}$	(-0.2 ± 2.0)
Bize et al	2004	$\frac{\text{Rb(hfs)}}{\text{Cs(hfs)}}$	$(0.1 \pm 1)^a$

[a] assuming $m_q/\Lambda =$ Const.

Combined results:

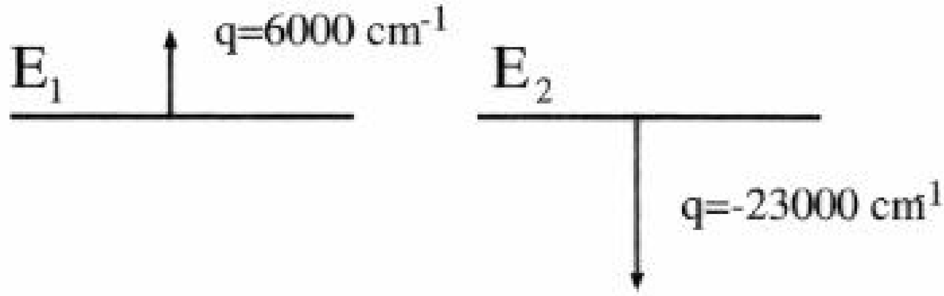
$$\frac{\partial \ln \alpha}{\partial t} = (-0.9 \pm 2.9) \times 10^{-15}\text{yr}^{-1}$$

$$\frac{\partial \ln (m_q/\Lambda_{QCD})}{\partial t} = (-4 \pm 10) \times 10^{-15}\text{yr}^{-1}$$

There is a possibility of 10^{10} times enhancement due to "degenerate" energy levels of different nature! Example: Dy atom.

1. $4f^{10}5d6s$, $E_1 = 19797.96...$ cm^{-1}
2. $4f^{9}5d^{2}6s$, $E_2 = 19797.96...$ cm^{-1}

Interval $\omega = E_2 - E_1 \sim 10^{-4}$ cm$^{-1} \sim 10^{-9}$E$_1$.



$$\omega = \omega_0 + (q_1 - q_2)2\frac{\Delta\alpha}{\alpha} =$$

$$= 10^{-4}\ \text{cm}^{-1} + 60000\ \text{cm}^{-1}\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta\omega}{\omega}(1\ \text{year})_{\text{Lab}} \sim \frac{\Delta\omega}{\omega}(10^{10}\ \text{years})_{\text{astro}}$$

Preliminary result: UC Berkely

$|\frac{\partial \ln\alpha}{\partial t}| < 4.3 \times 10^{-15}\text{yr}^{-1}$

CONCLUSIONS

BBN/CMB data may be interpreted as variation of $\mathbf{m}_q/\Lambda_{QCD}$.

MM method provided sensitivity increase $\sim$100 times. Many lines, positive and negative shifters - control of systematics.
Keck data- 3 independent optical samples, 143 systems- variation of α.
VLT data- no variation.
Undiscovered systematics or spatial variation?

$\mathbf{m}_e/m_p$: 21 cm H/optical- no variation;
H_2 (Paris-Amsterdam-Peterburg)-variation!

Oklo data: variation of $\mathbf{m}_q/\Lambda_{QCD}$!?

- Atomic clocks are very sensitive to present time variation of α and $\mathbf{m}_q/\Lambda_{QCD}$. Transition between close levels - a billion times enhancement.